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(54) **INTEGRATED PARTICLES SENSOR FORMED ON SINGLE SUBSTRATE USING FRINGES FORMED BY DIFFRACTIVE ELEMENTS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 544 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/838,344**

(22) Filed: **Sep. 15, 2000**

Related U.S. Application Data

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(51) **Int. Cl.**[7] **G01N 21/49**

(52) **U.S. Cl.** **250/574**; 356/336; 356/441; 73/865.5; 73/705

(58) **Field of Search** .... 356/35, 49, 335–342, 356/354, 28, 442; 73/865.5, 147, 705; 250/550, 237 G, 222.2, 224, 573, 574

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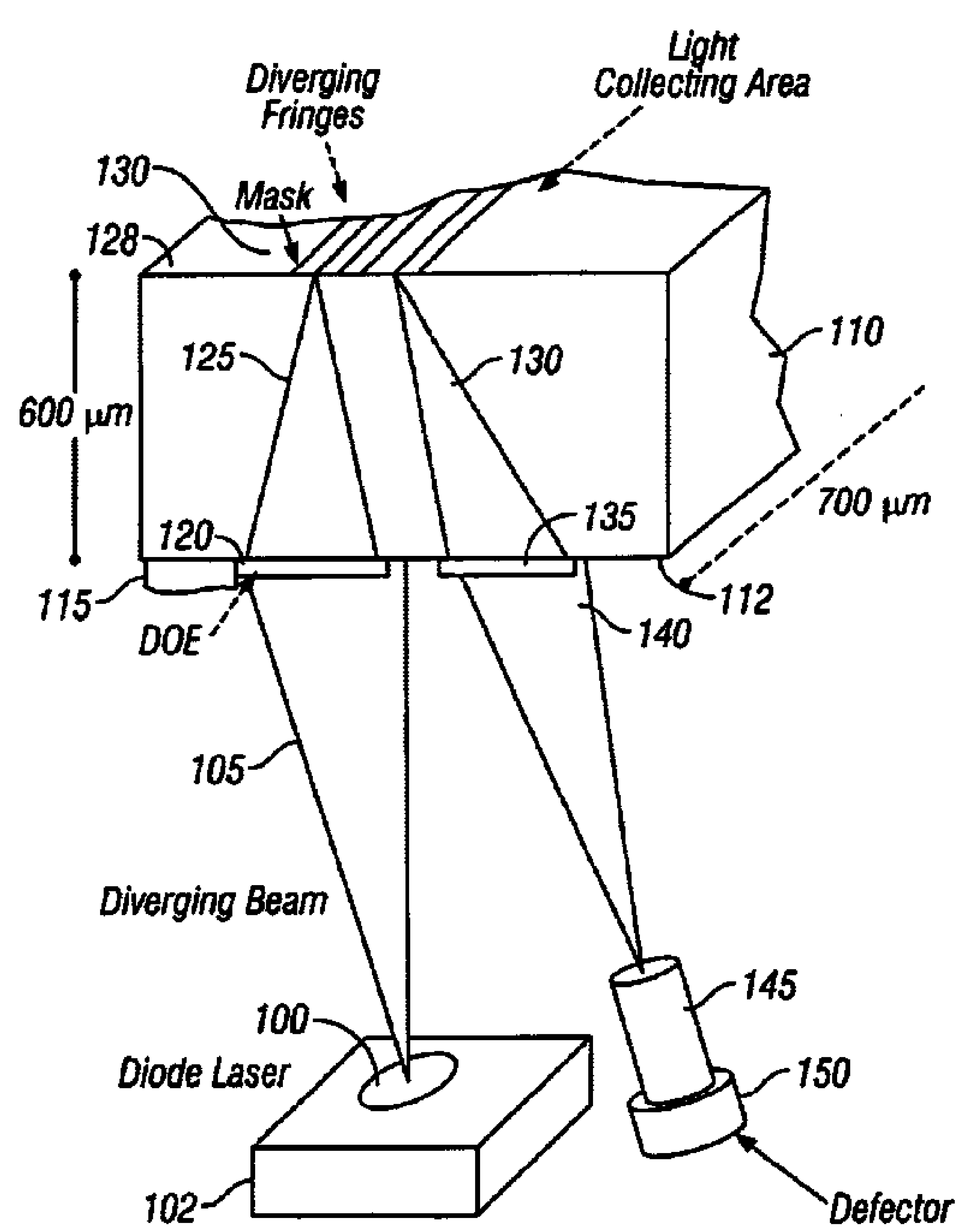
(57) **ABSTRACT**

Integrated sensors are described using lasers on substrates. In one embodiment, a first sensor forms a laser beam and uses a quartz substrate to sense particle motion by interference of the particles with a diffraction beam caused by a laser beam. A second sensor uses gradings to produce an interference. In another embodiment, an integrated sensor includes a laser element, producing a diverging beam, and a single substrate which includes a first diffractive optical element placed to receive the diverging beam and produce a fringe based thereon, a scattering element which scatters said fringe beam based on particles being detected, and a second diffractive element receiving scattered light.

24 Claims, 8 Drawing Sheets



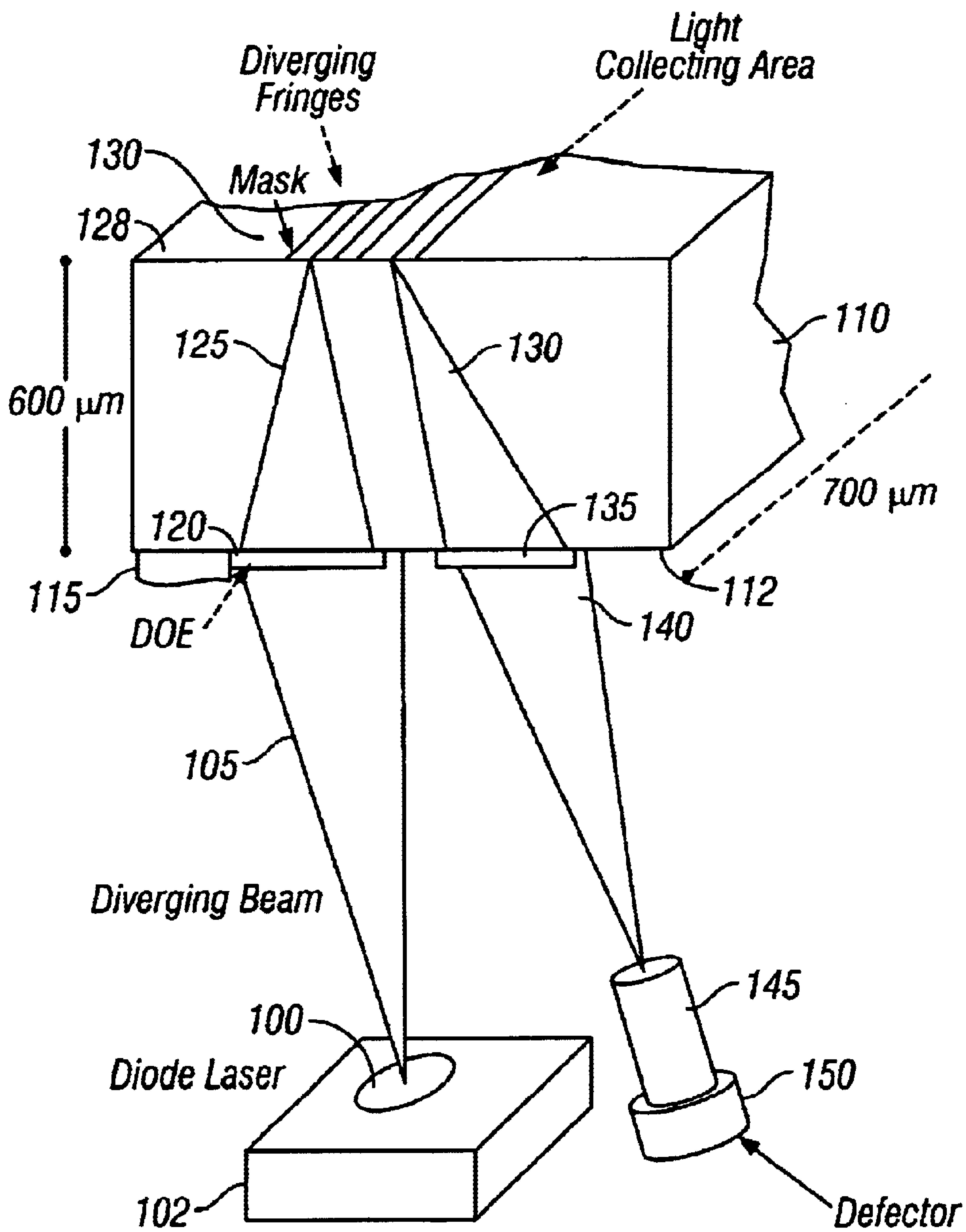

Light
Collecting Area
Diverging
Fringes
130
Mask
128
600 μm
125
130
110
700 μm
120
135
115
DOE
112
140
105
Diverging Beam
145
100
Diode Laser
150
102
Defector

FIG. 1

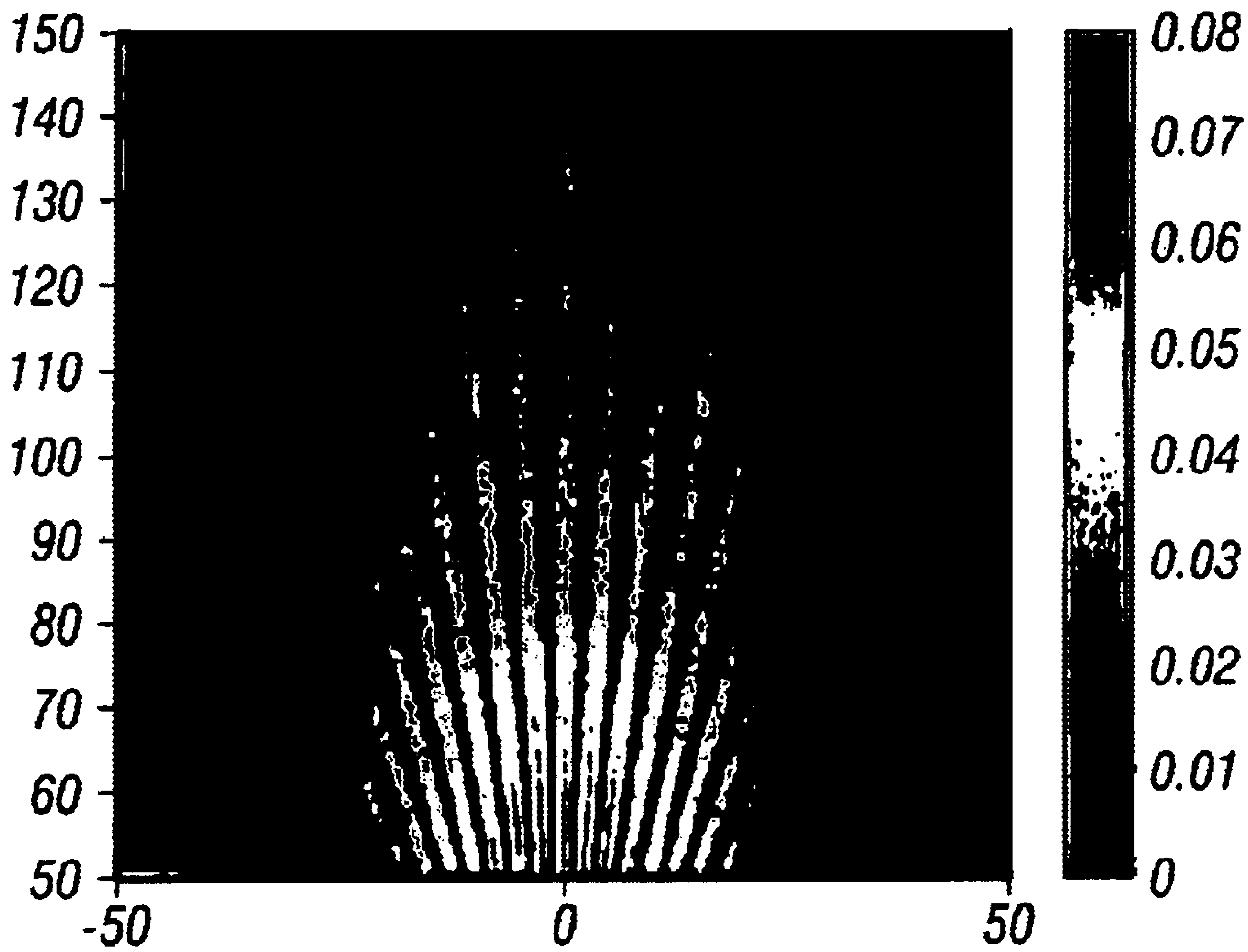

150
140
130
120
110
100
90
80
70
60
50
-50
0
50
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

FIG. 2

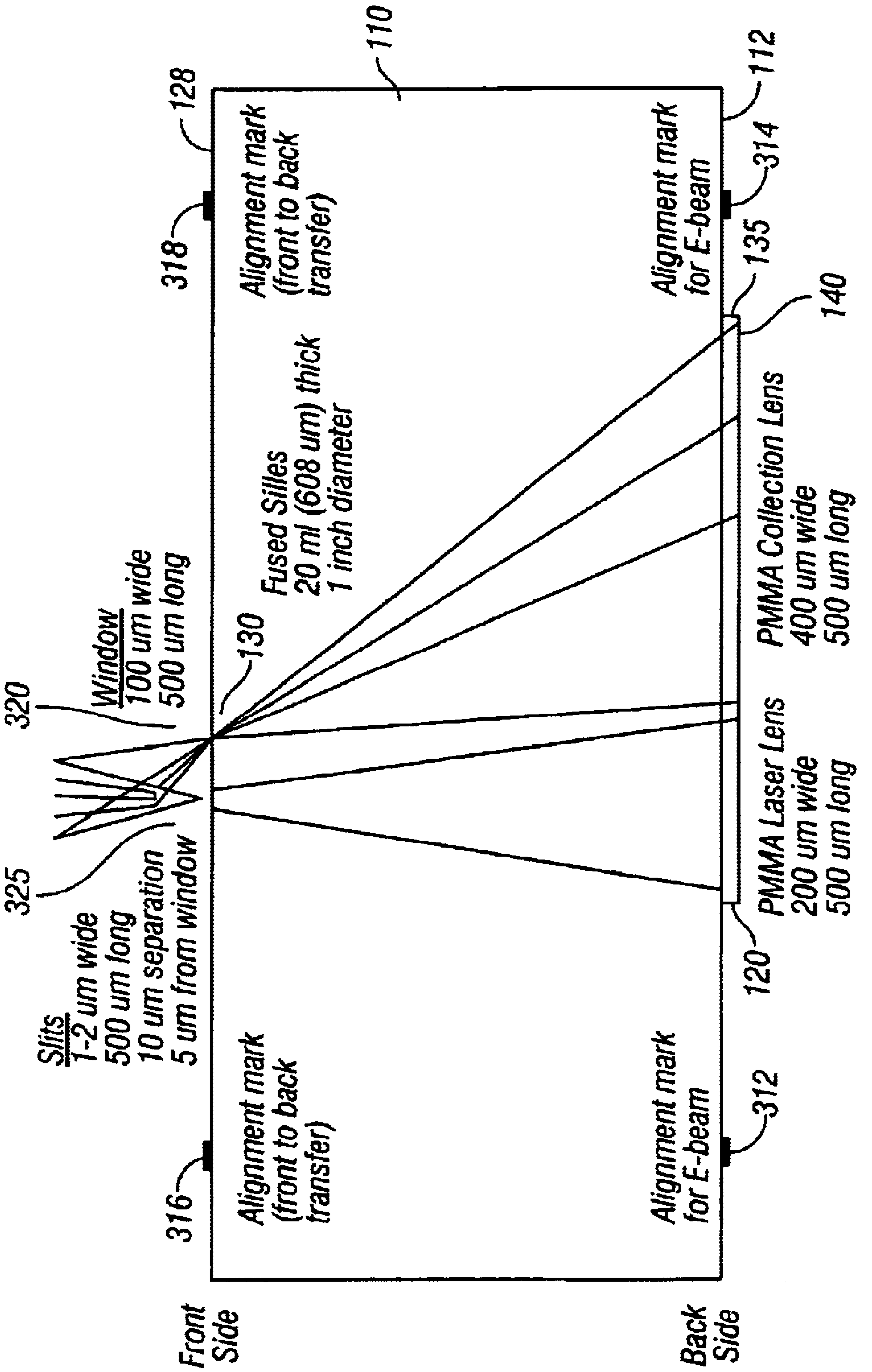

110
128
112
318
314
135
140
316
312
320
325
130
120
Alignment mark (front to back transfer)
Alignment mark for E-beam
Fused Silles
20 ml (608 um) thick
1 inch diameter
Window
100 um wide
500 um long
Slits
1-2 um wide
500 um long
10 um separation
5 um from window
PMMA Collection Lens
400 um wide
500 um long
PMMA Laser Lens
200 um wide
500 um long
Alignment mark (front to back transfer)
Alignment mark for E-beam
Front Side
Back Side

FIG. 3

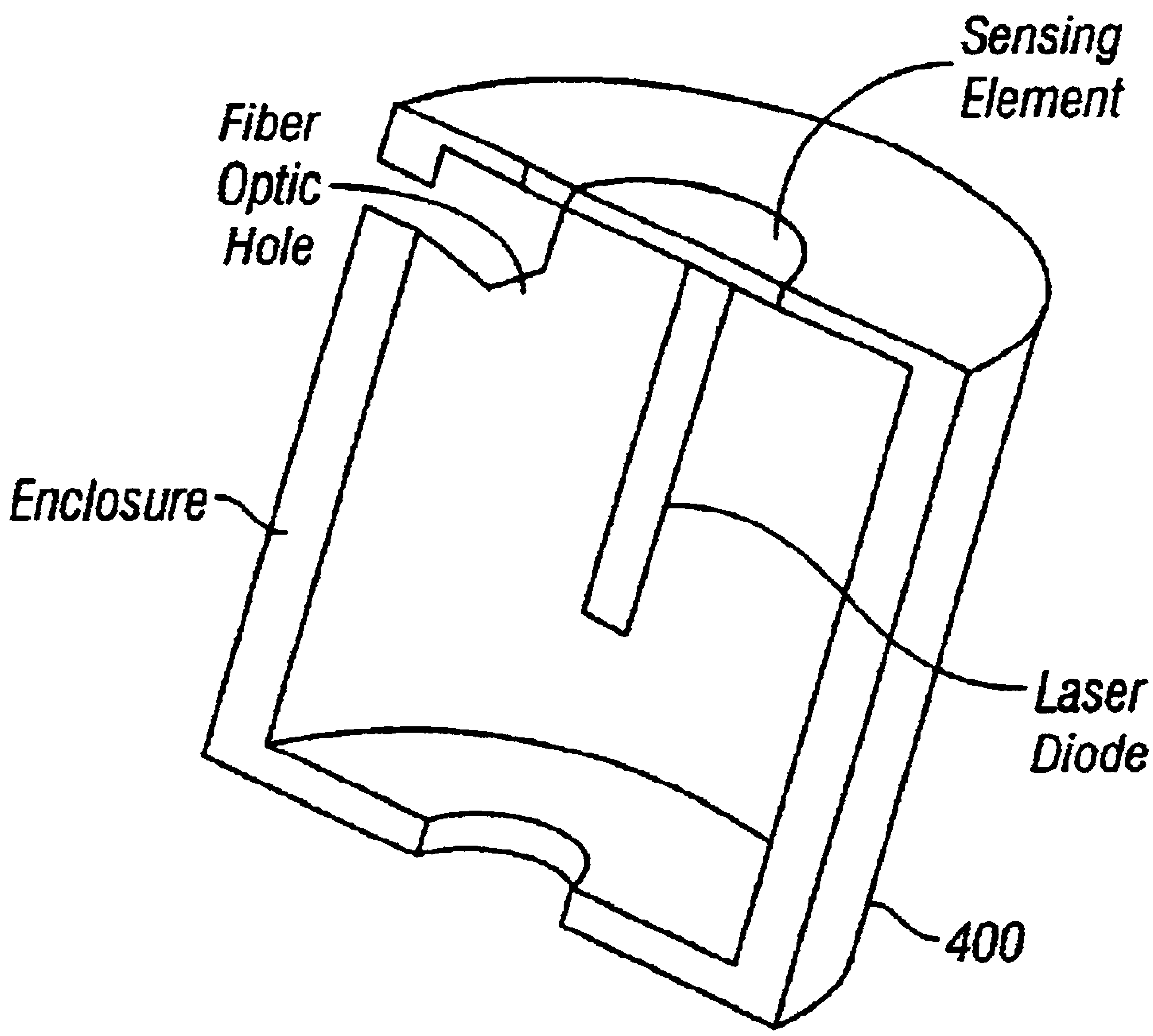

Sensing
Element
Fiber
Optic
Hole
Enclosure
Laser
Diode
400

FIG. 4

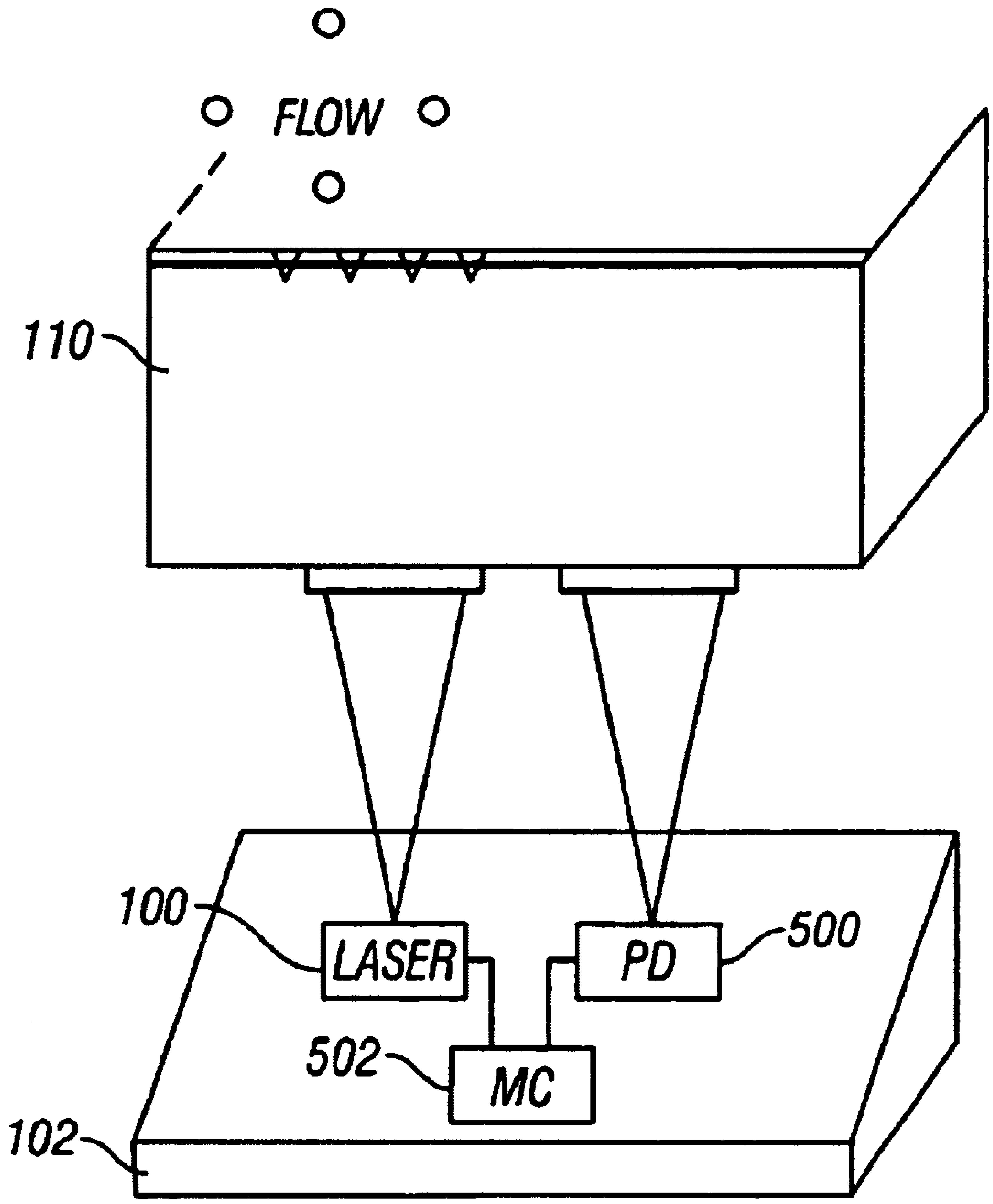


FIG. 5

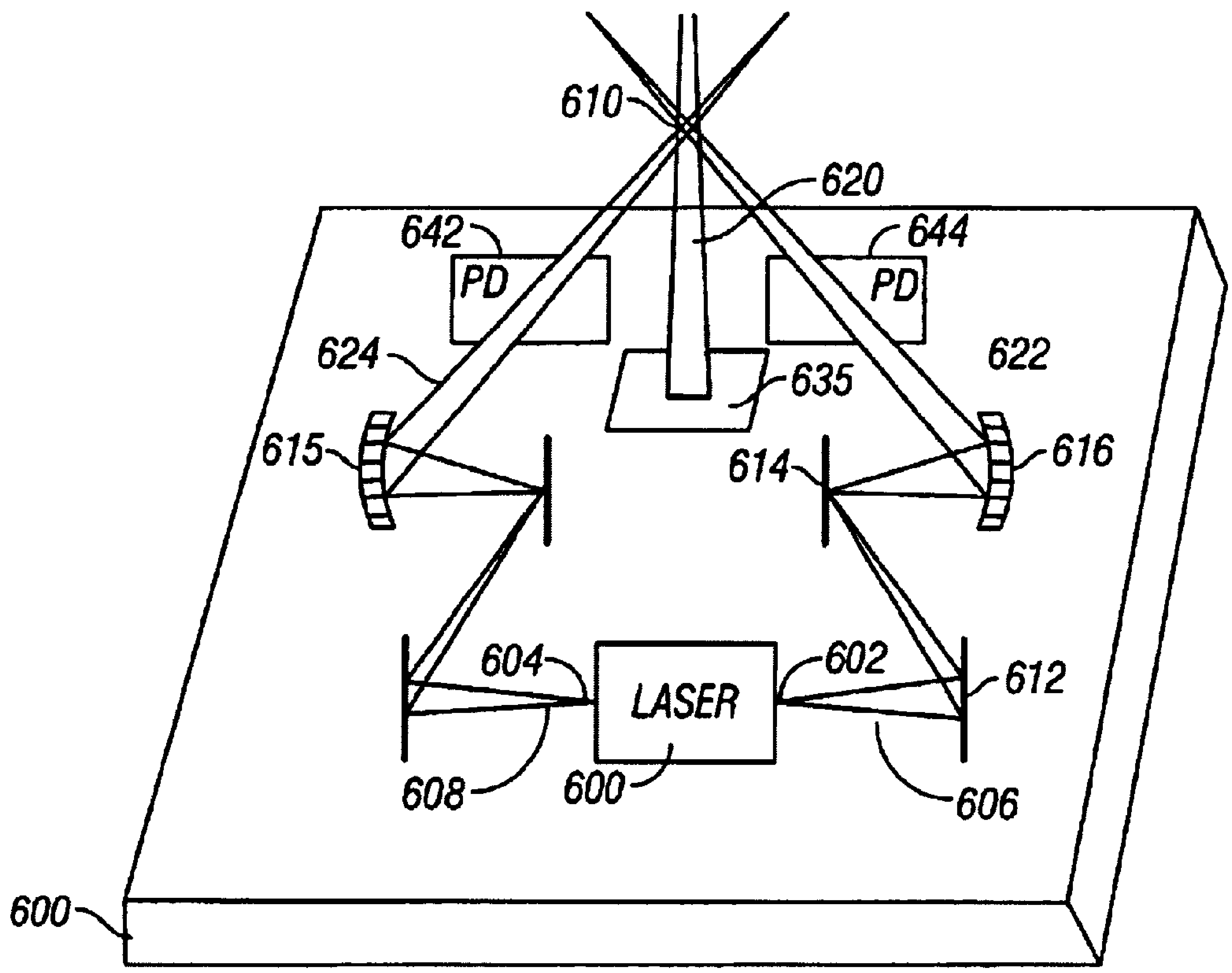

610
620
642
644
PD
PD
624
622
635
615
616
614
604
602
LASER
612
608
600
606
600

FIG. 6A

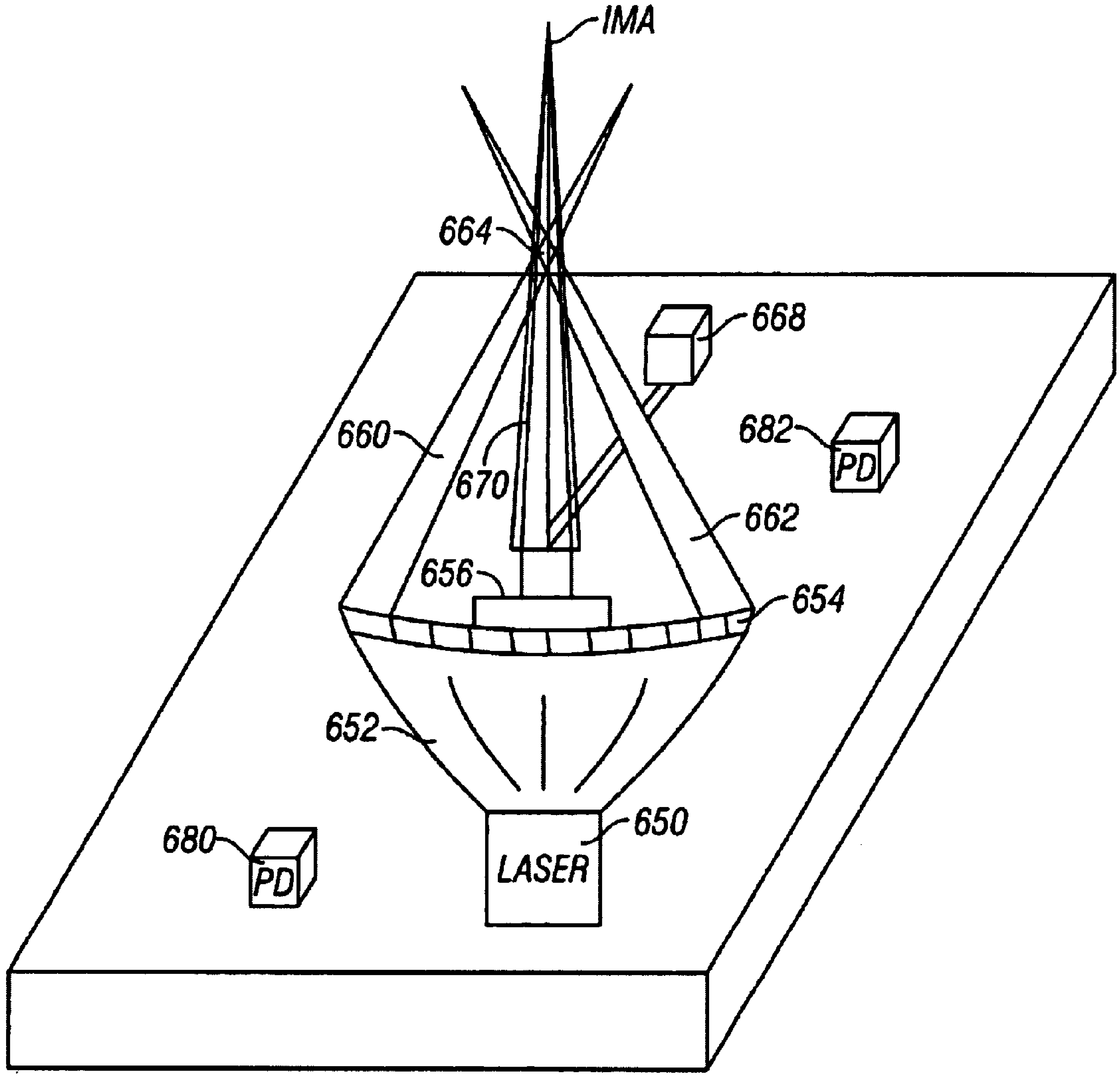


FIG. 6B

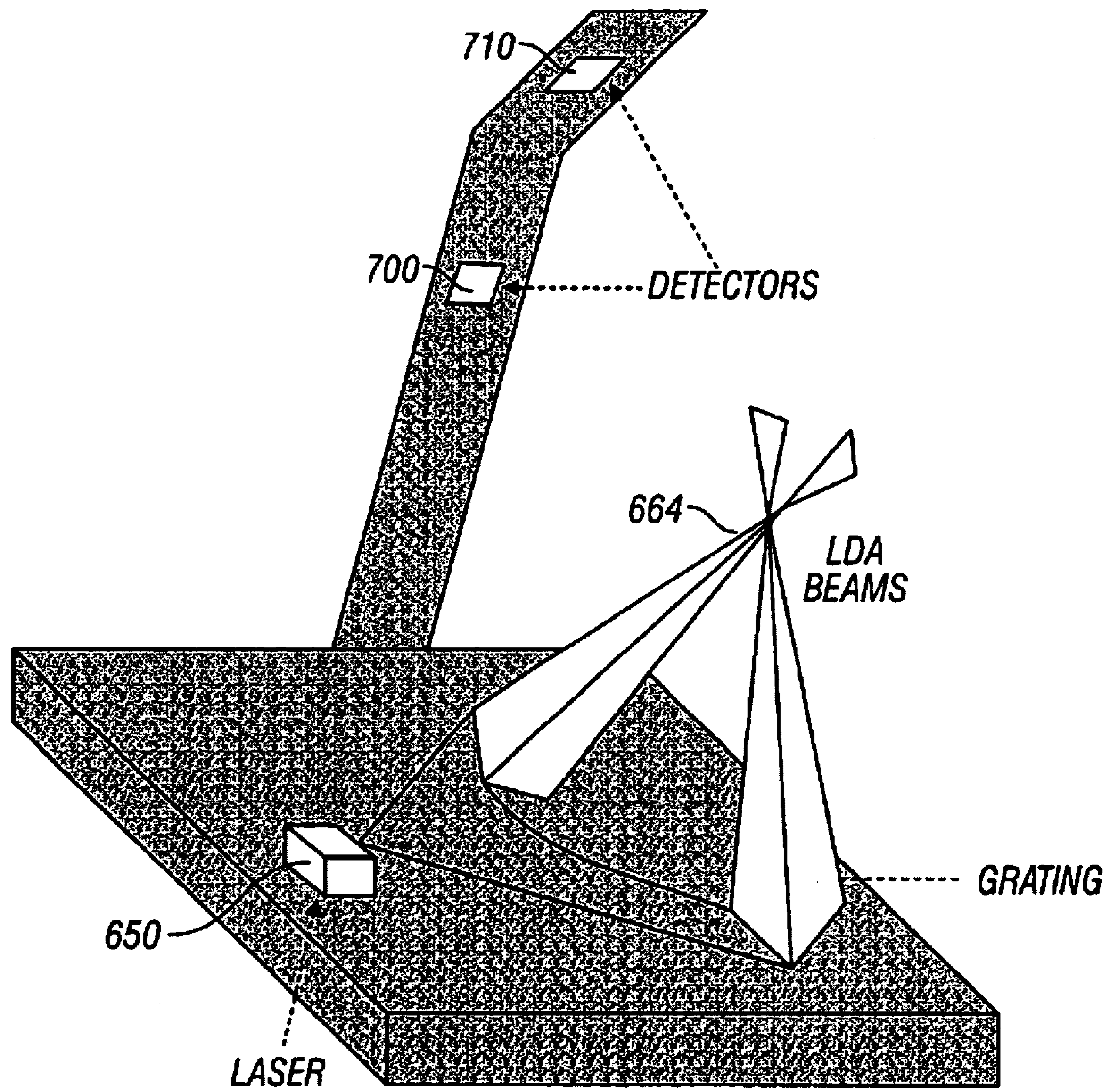


FIG.7

INTEGRATED PARTICLES SENSOR FORMED ON SINGLE SUBSTRATE USING FRINGES FORMED BY DIFFRACTIVE ELEMENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of U.S. Provisional application No. 60/154,486, and No. 60/154,487, both filed Sep. 17, 1999.

STATEMENT AS TO FEDERALLY-SPONSORED RESEARCH

U.S. Government may have certain rights in this invention pursuant to Darpa grant number N66001-99-1-8902 and U.S. Navy grant no. N00014-99-1-0297.

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (U.S.C. 202) in which the contractor has elected to retain title.

BACKGROUND

It is often desirable to obtain different kinds of information about particles.

One kind of information is about shear stress. An existing method of detecting wall shear stress puts a heated wire or element in the flow to be detected. The rate of cooling of the element provides a measure of the wall shear stress. Other similar sensors, which sense other parameters, are also known.

However, this system by itself has certain problems. The techniques may be intrusive, meaning that they may effect the rate of flow. The techniques can be affected by contaminants in the flow. For example, certain contaminants may deposit on the heated element and cause the heated element to react differently. These techniques can also change the characteristics of the sensor; hence requiring calibration.

Non-intrusive optical techniques may be considered using conventional optics. However, this results in a bulky setup, and setup that is highly susceptible to vibration. Moreover, the size of such a setup may cause difficulty in allowing the system to be effectively used.

Other kinds of probes can be used to detect the size of particles, and may have similar drawbacks.

SUMMARY

The present application teaches integrated optical sensors for detecting particle details.

One aspect detects and/or measures wall shear stress in flows.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects will now be described in detail with reference to the accompanying drawings wherein:

FIG. **1** shows a schematic for a first wall stress sensor;

FIG. **2** shows an optical fringe pattern emitted by the sensor of FIG. **1**;

FIG. **3** shows a details of fabrication of the optical part;

FIG. **4** shows an assembly drawing showing the way in which the elements are held within a housing;

FIG. **5** shows another embodiment using a common substrate to support the laser and the optical detector.

FIGS. **6**A and **6**B show two embodiments of integrated optical sensors.

FIG. **7** shows an integrated optical sensor based on a phased Doppler technique.

DETAILED DESCRIPTION

The present application teaches a special miniaturized and integrated optical sensor probe for measuring wall shear stress in aerodynamic and hydrodynamic flows for example. As described herein, the system also provides structure which is highly minaturizable, and which can be formed within a housing of a special type that enables the use of the sensor in harsh environments. Moreover, the system in is non-intrusive and non-invasive. The center of the probe's volume may be located very close to the surface being measured, e.g. as close as 100 microns to the surface. Moreover, the sensor as described herein may be configured in a way, as described herein, that may require less calibration.

A schematic of the sensor is shown in FIG. **1**. A diode laser **100** is formed on a substrate **102**. The diode laser produces a diverging output beam **105** which diverges at a specified angle. The output beam is shaped, for example, into two, parallel very high aspect ratio ellipses. The beam is coupled toward a transparent substrate, e.g., a quartz substrate **110** which forms an optical assembly. The quartz substrate may have a size, for example, of 600 microns thick and 700 microns square on a side. The quartz substrate **110** includes a metal film **115** formed thereon, e.g., a film formed of chromium or aluminum. The metal film is processed to form specified openings therein. Optical slits are formed in an area **120** of the metal film, arranged to form a diffractive optical element. The slits can be fabricated by etching the metal from the thin film in a specified pattern.

The light exiting from the diffractive optical element **120** forms a two-dimensional, linearly diverging optical fringe pattern **125**. The optical fringe pattern can, for example, simply include diverging fringes. The fringe pattern may be of the type shown in FIG. **2** where the pattern width is on the order of 25 microns, and the position is on the order of 90 microns for the main part of the fringe, with the edges of the fringe ending at 130–140 microns.

The fringe **125** impinges on a mask **130** which is formed on the second surface **128** of the quartz substrate **110**.

The second surface **128** of the quartz substrate is placed near the flow to be measured. Light is scattered off the particles crossing the fringe pattern to form reflected beam **130**.

Scattered light is also obtained by a second optical window **135** that is formed in the metal film **115**. The light is collected through that optical window, via another diffractive optical element **140** formed on the surface of the quartz element. The scattered light is collected by those elements and focused onto an optical fiber detector **145**. An avalanche photodiode **150** can be located at the end of the detector, receiving the light therefrom.

An important feature of system in FIG. **1** is that the sensor element can be fabricated using micro-fabrication technology. The substrate **110** can be formed as shown in FIG. **3**. The surface **112** includes the laser "lens" **120**, and the collection lens **130**, **140**. The other side **128** of the substrate includes a plurality of slits. In addition, both sides of the substrates include alignment marks. **112** include the alignment marks **312**, **314**, which are alignment marks for the electronic beams. The front side **128** includes the alignment marks **316**, **318** which are the alignment for the front-to-back transfer.

The substrate may be fabricated as follows. A quartz substrate of size 2 mm×2 mm×0.5 mm is obtained. The quartz substrate can be fused silica, for example. The substrate is first evaporatively coated with a thin film of chromium using evaporation. The result in structure is then coated with polymethylmetachrylate or PMMA.

Slits **130** are opened in the front side **128**. This can be formed as two different openings, e.g., a first window **320** which is 100 microns wide and 500 microns long. A plurality of slits **325** are formed to the side of that window. These can be 1–2 microns wide, and 500 microns long. The slits have 10 micron separations from one another, and may be separated by 5 microns from the window **320**. The slits and optical window pattern can be opened in the PMMA using e-beam lithography. The chromium may be subsequently wet edged in the open areas to form better openings.

Thereafter, the surface is coated with a thick layer of photoresist in order to protect the surface. The back side **112** is also coated with photoresist. The front side alignment marks are used to form front side holes and open holes in the photoresist using an optical mask and UV exposure. The surface is then coated with metal for liftoff. The metal is removed using E-beam alignment marks. All of the photoresist can also be removed.

A PMMA layer is then deposited on the bottom of substrate **112**. Two different diffractive optical elements are formed in the PMMA layer. The PMMA laser lens **120** is formed which is 200 microns wide 500 microns long. The PMMA collection lens **135** is formed that is 400 microns wide 500 microns long. These are formed using E-beam lithography and developed using acetone.

The sensing element is then formed and mounted in a housing **400**. The housing **400** includes all of the structure therein, including the diode laser and optical receiver.

This system can produce significant advantages. In addition, modifications in this system are contemplated. For example, a diffractive optical element can be used in place of the optical window **320** in order to collect the scattered light more efficiently.

In another embodiment, shown in FIG. **5**, the detector is mounted directly on the substrate **102**. This avoids the use of fibers, and reduces the parts count. In this embodiment, both the laser **100**, and photodiode **500** are mounted on a single substrate **102**. A controller **502** may also be mounted on the substrate. The controller may control both the laser **100** and the photodiode **500**. For example, the controller can instruct the laser what and when to emit. It can receive information from the photodiode, and interpret it in view of timing information sent to the laser.

Another embodiment which forms a fiber optic particle probe is shown in FIGS. **6A** and **6B**. A diode laser is used along with curved gratings and detectors. FIG. **6A** shows a configuration with a laser **600** emitting along both sides **602** and **604**. The two-sided emission provides laser output arms **606**, **608**. Beam **606** is reflected by mirrors **612**, **614**, and coupled to a curved grating **616**. Beam **608** is correspondingly coupled to grating **618**. The outputs **622**, **624** of gratings **616**, **618** are recombined off the surface at a point **610**. The point **610**, for example, can be 3 millimeters over the surface of the substrate **600**. A fringe pattern is formed by the recombination.

The fringe pattern is centered on a second laser beam, called the IMAX beam, that has been created by a second laser source **635**. The IMAX beam provides information on the size of the particle and as such is a particle-sizing beam **620**.

Light is scattered by the particles and received by photodetectors **642**, **644**, which are mounted on the substrates in locations to receive the scattered light from the particles at the point **610**. The phase shift of the detectors is proportional to the particle size at the point **610**. An on-chip or off processor or controller may receive the signals from the photodetectors and calculate the particle size.

FIG. **6B** shows an alternative embodiment in which fringes in space are formed. A single ended diode **650** produces an output **652**. The diode laser output **652** is allowed to diverge onto a curved grating **654**, which is blocked in its center shown as **656**.

The grating **654** redirects the light **652** into two separated light beams **660**, **662**, which are separated by the blocked portion **656**. The two light beams **660** and **662** are directed to intersect 3 millimeters off the surface at the point **664**. A separate laser **668** produces an IMAX beam **670**. As in the FIG. **6A** embodiment, photodetectors **680**, **682** detect the scattered light and use the scattered light to find particle size.

Another embodiment shown in FIG. **7** uses a phased Doppler technique without the technique using the IMAX beam. The same structure of the laser **650** and curved grating **654** forming the LDA beams intersecting above the surface is defined. Detectors **700**, **710** are located on an arm extending above the surface to receive the beam. This technique works best for particle sizes close to the laser wavelength.

As in the other embodiments, the scattered light gathered by the two detectors exhibits a phase shift that is proportional to the phase particle size.

Although only a few embodiments have been defined in detail above, other modifications are possible.

What is claimed is:

1. A sensor, comprising:

a laser element, producing a diverging beam; and

a single substrate, including a first diffractive optical element placed to receive the diverging beam and to produce a fringe beam based thereon, a mask with openings placed to receive the fringe beam from the first diffractive optical element and to interface with particles being detected which scatter said fringe beam, and a second diffractive element receiving scattered light.

2. A sensor as in claim **1**, wherein said single substrate includes a first surface which includes both said first and second diffractive optical elements.

3. A sensor as in claim **2**, further comprising a second surface, opposite said first surface, including a pattern formed thereon which receives particles crossing the pattern, and light crossing the particles being collected as said scattered light.

4. A sensor as in claim **1**, further comprising a detector, receiving said scattered light, and producing a signal indicative of a property of particles being detected.

5. A sensor as in claim **4**, further comprising a housing, wherein said laser element, said single substrate, and said detector are coupled within said housing.

6. A sensor as in claim **1**, wherein said substrate is a substrate formed of a quartz.

7. A sensor as in claim **1**, wherein a dimension of each side of said quartz substrate is less than 1000 microns.

8. A sensor as in claim **6**, wherein said quartz substrate has a first surface with said first and second diffractive optical elements formed thereon and a second surface with diverging fringes which is placed in an area of light collection.

9. A method of measuring particles, comprising:

placing a first surface of a transparent substrate into contact with a source of particles;

illuminating said particles with a laser via a diffractive optical element on a second surface of said substrate to form interference fringes and receiving scattered light from said particles via a second diffractive element; and

monitoring said received light to determine information about said particles.

10. A method as in claim **9**, wherein said diffractive elements are formed by depositing PMMA on the surface of the substrate.

11. A method as in claim **9**, wherein said substrate is formed of quartz.

12. A method as in claim **9**, further comprising forming alignment marks on opposite sides of the substrate.

13. A method as in claim **12**, wherein said alignment marks are formed as positive structures on one side, and lack of positive structures on the other side.

14. An integrated shear stress sensor, comprising:

a housing;

a laser diode coupled to said housing in a location to emit light;

a sensing element, formed by a transparent substrate, having a first surface adjacent said laser diode to receive illumination therefrom and a second surface adjacent a top portion of said housing to sense particle movement; and

an optical sensor, also coupled to said housing, coupled adjacent to said substrate to receive collected light therefrom; and

optical slits on the second side of the substrate forming a fringe pattern in an area of said second side of said substrate, said fringe pattern interfering with said particles.

15. A sensor as in claim **14**, wherein said first surface of said substrate includes two diffractive optical elements, a first optical element receiving said laser beam from said laser diode, and a second of said optical elements receiving collected light.

16. A sensor as in claim **15**, wherein said diffractive optical elements are formed from PMMA layers on the substrate.

17. A sensor as in claim **14**, wherein said optical sensor includes an avalanche photodiode.

18. A method of sensing particles, comprising:

illuminating particles with laser light via a series of slits which form a fringe pattern; and

detecting interference with said fringe pattern as detecting particle flow.

19. A method as in claim **18** wherein said detecting comprises extracting shear stress information from the interference.

20. A method as in claim **18**, further comprising directing an additional laser beam to the particles to detect a size of the particles.

21. A method as in claim **18**, wherein said illuminating comprises forming two beams, and recombining said two beams to form said fringe pattern.

22. A method as in claim **21**, wherein said two beams are formed by a laser producing two output beams.

23. A method as in claim **21**, wherein said two beams are formed by a single grating with a blocked part.

24. A method as in claim **18**, wherein said detecting comprises detecting light in two locations, and determining a phase shift therebetween.

* * * * *